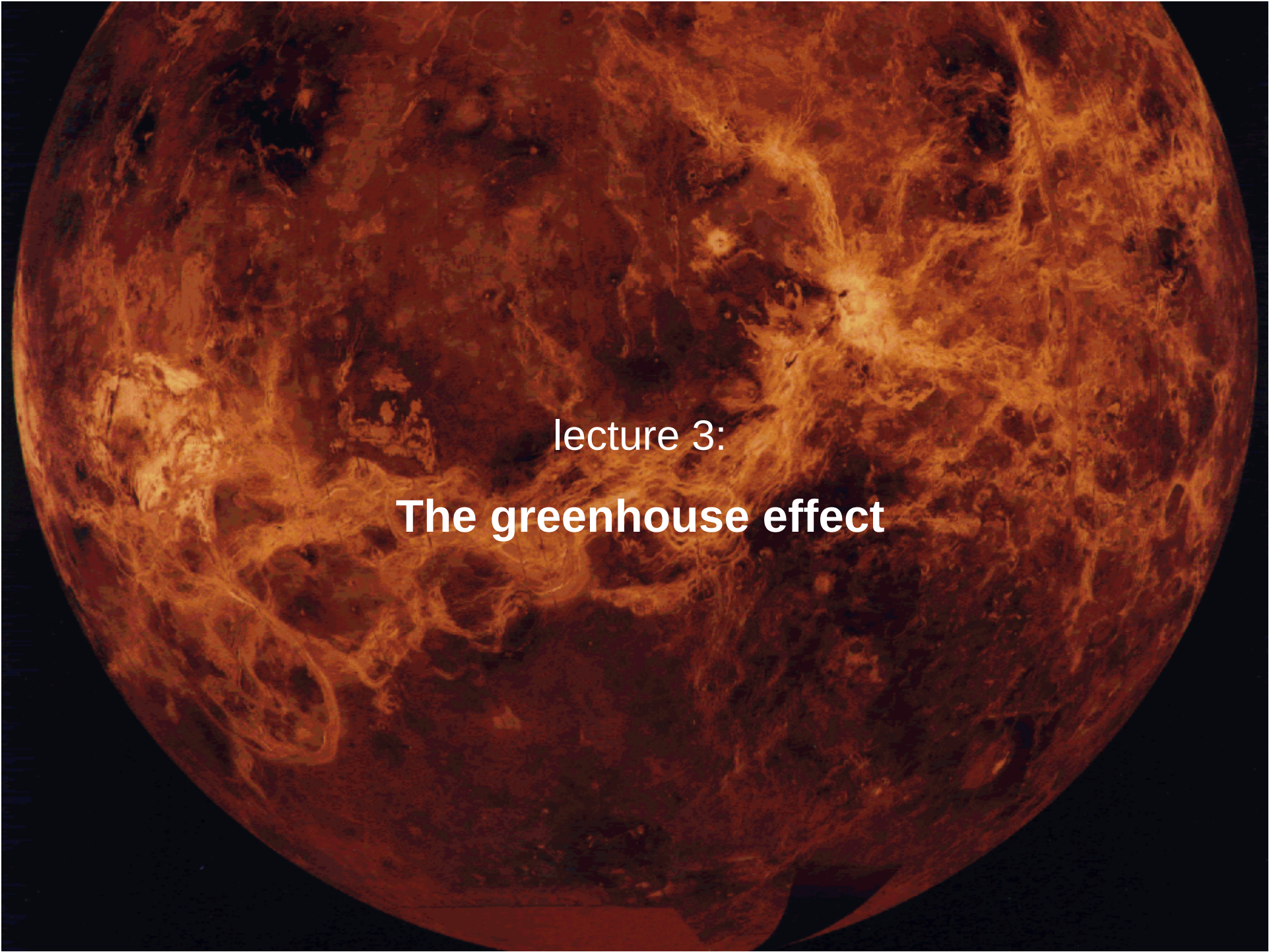




lecture 3:

The greenhouse effect

VISIT...

LANZAROTE
Caliente.COM

Concepts from Lecture 2

Temperature Scales

Forms of Heat Transfer

Electromagnetic Spectrum

Planck Law

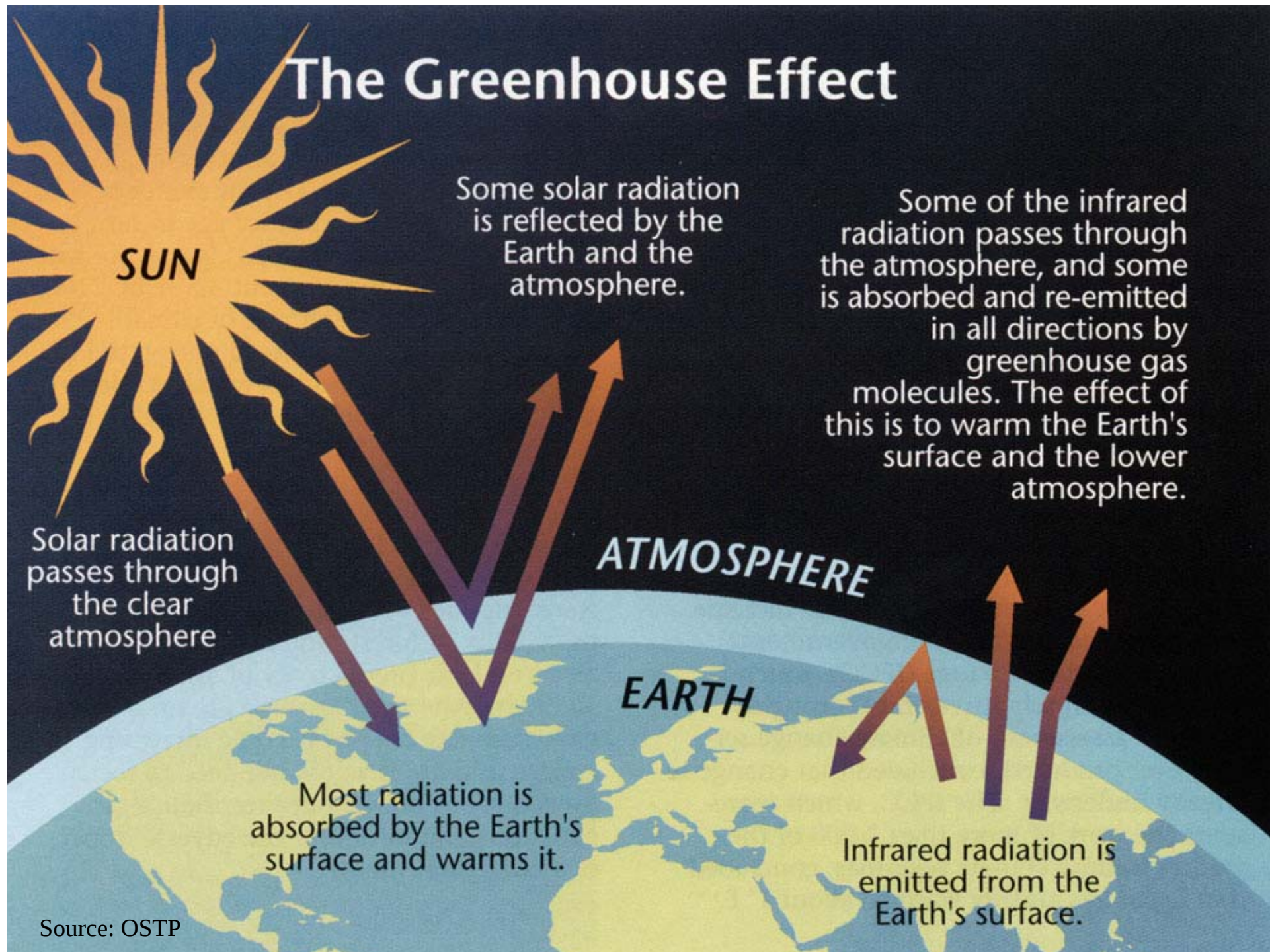
Stefan-Boltzmann Law

Inverse Square Law

Reflectivity or Albedo

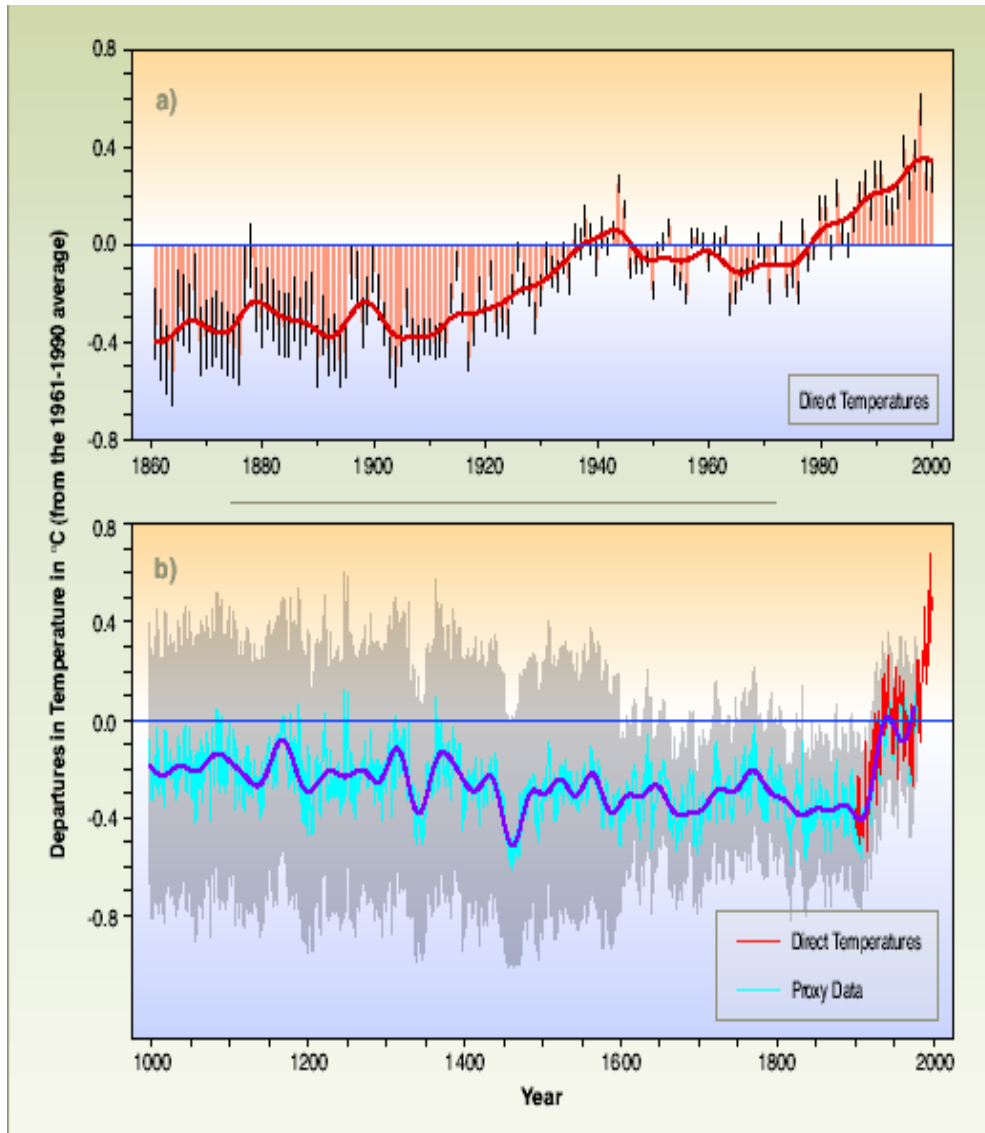
**Solar (Shortwave) and Terrestrial (Longwave)
Radiation**

The Greenhouse Effect

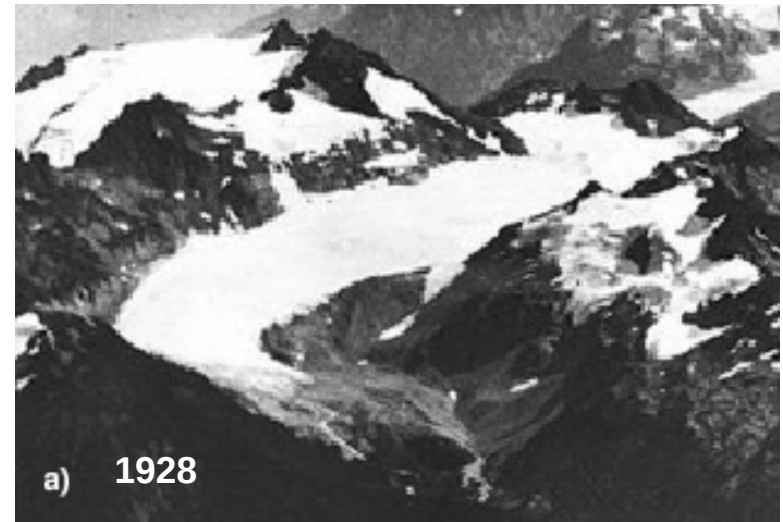


Source: OSTP

Strong Evidence for Global Warming

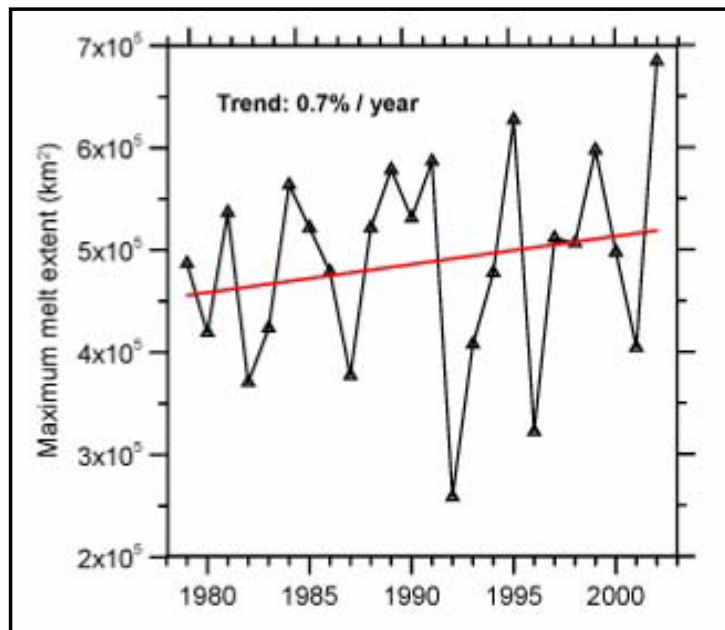


From US Climate Change Science Program

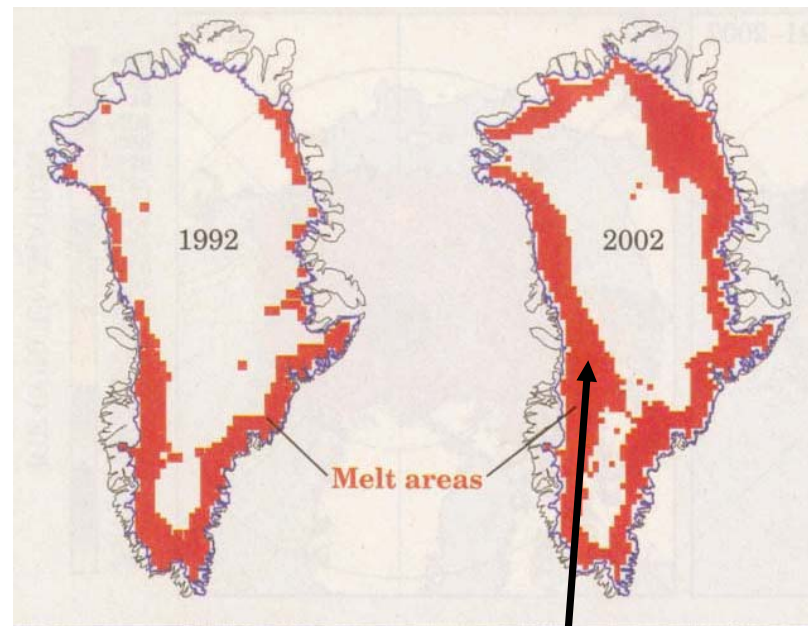


South Cascade Glacier, Washington

Increasing Melt Area on Greenland



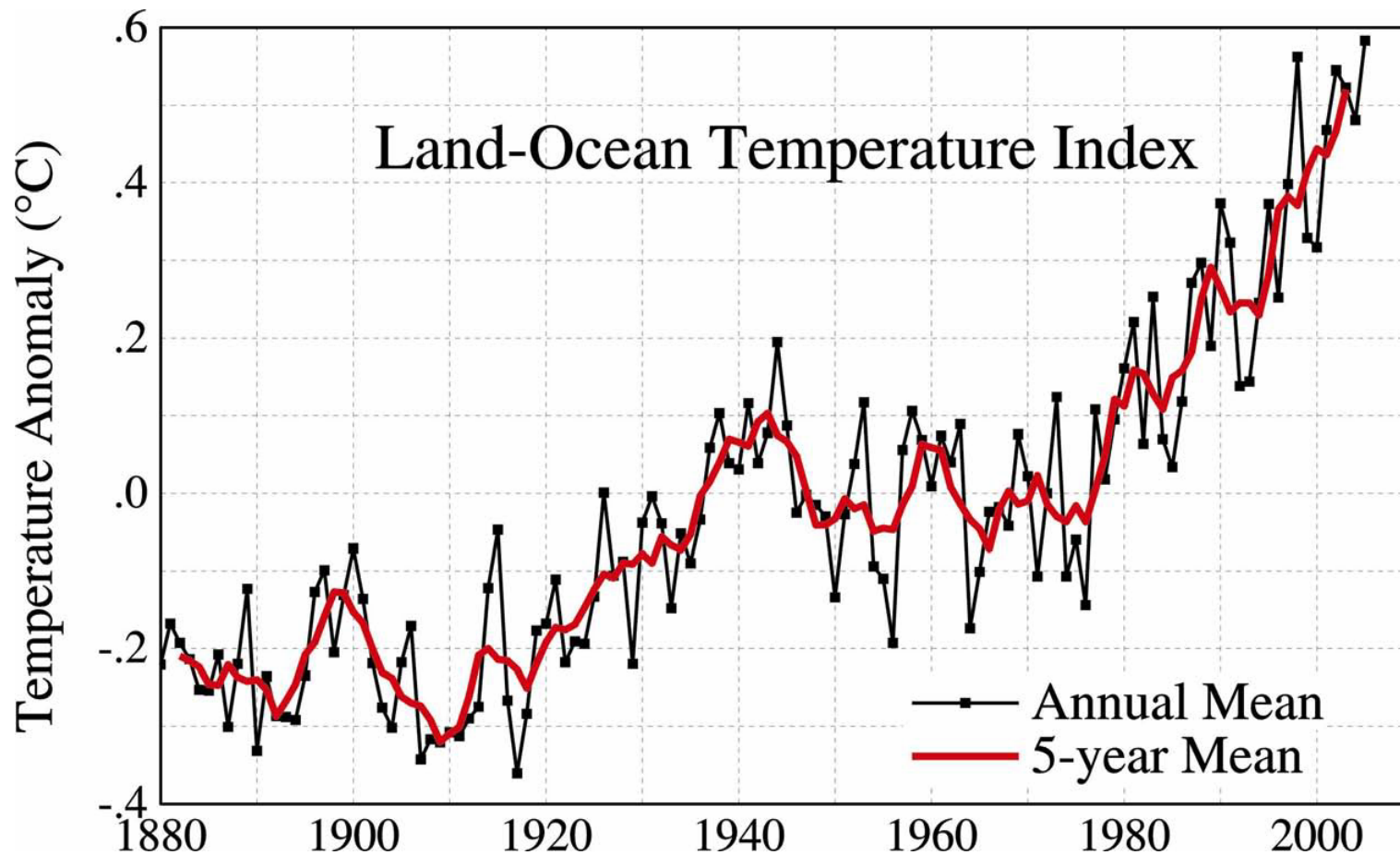
- 2002 all-time record melt area
- Melting up to elevation of 2000 m
- 16% increase from 1979 to 2002



70 meters thinning in 5 years

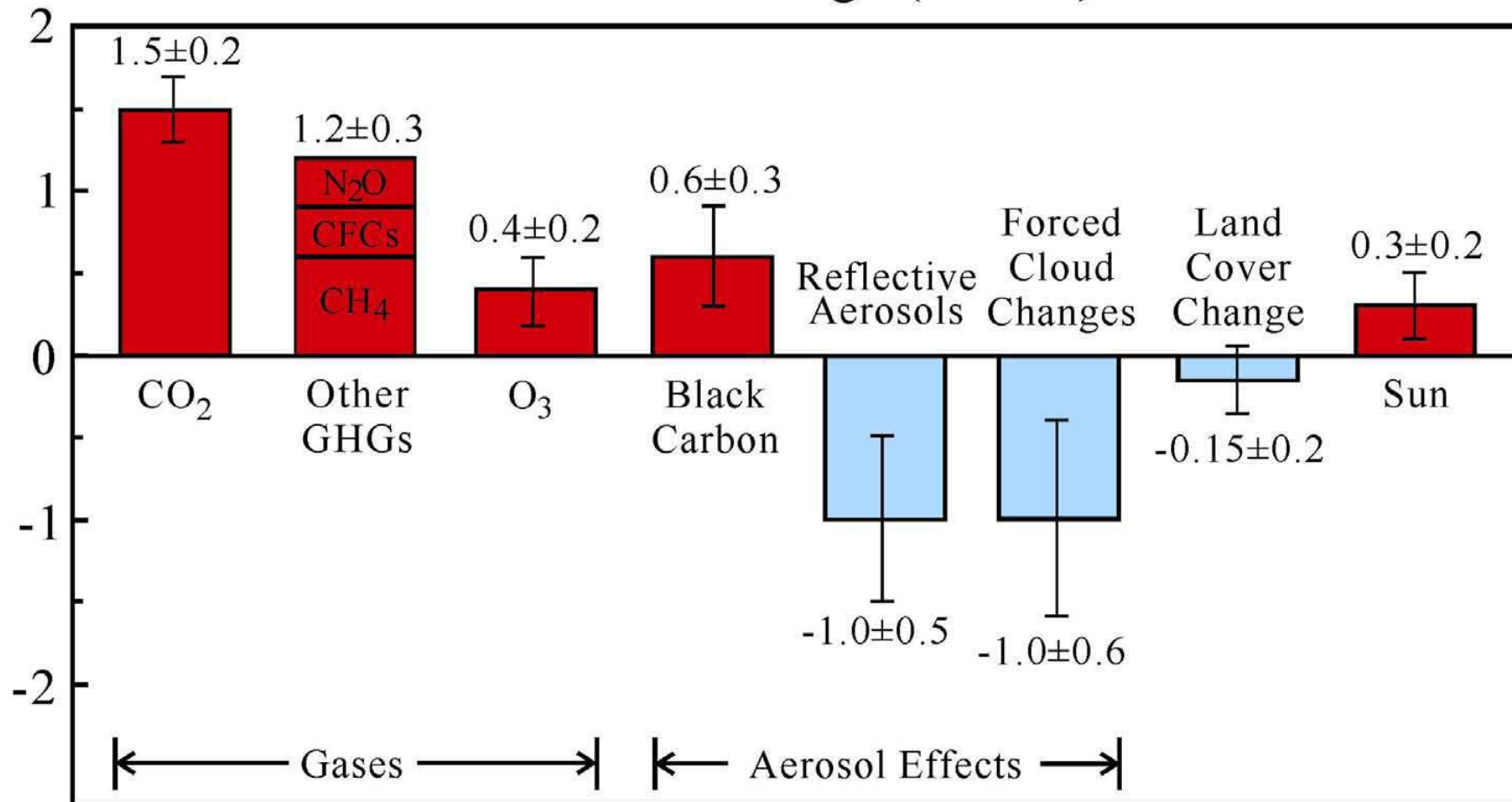
Satellite-era record melt of 2002 was exceeded in 2005.

Source: Waleed Abdalati, Goddard Space Flight Center



Global mean surface temperature change based on surface air measurements over land and SSTs over ocean. *Source:* Update of Hansen et al., *JGR*, 106, 23947, 2001; Reynolds and Smith, *J. Climate*, 7, 1994; Rayner et al., *JGR*, 108, 2003 (after James E. Hansen 2006).

Effective Climate Forcings (W/m^2): 1750-2000



Climate forcing agents in the industrial era. “Effective” forcing accounts for “efficacy” of the forcing mechanism

Source: Hansen et al., JGR, **110**, D18104, 2005.

The greenhouse effect of Venus

From geometry, we can calculate the average solar flux over the surface of Venus. It is approximately **661 W/m²**.

Venus is very reflective of solar radiation. In fact, it has a reflectivity (or albedo) of 0.8, so the planet absorbs approximately $661 \times 0.2 =$ **132 W/m²**.

By assuming that the incoming radiation equals the outgoing radiation (**energy balance**), we can convert this into an effective radiating temperature by invoking the Stefan-Boltzmann law (total energy = σT^4). We find that **T=220 K**.

But Venus' surface has a temperature of **730 K!!!**

The explanation for this huge discrepancy is the planet's greenhouse effect.

The greenhouse effect of Earth

From geometry, we can calculate the average solar flux at the top of the atmosphere. It is approximately **343 W/m²**.

The earth has a much lower albedo than Venus (0.3), so the planet absorbs approximately $343 \times 0.7 =$ **240 W/m²**.

By assuming that the incoming radiation equals the outgoing radiation, we can convert this into an effective radiating temperature by invoking the Stefan-Boltzmann law (total energy = σT^4). We find that **T=254 K**.

Earth's surface has a temperature of **288 K**

While much smaller than Venus' greenhouse effect, Earth's is crucial for the planet's habitability. Without the greenhouse effect, the temperature today in Los Angeles would be about 0 degrees Fahrenheit.

Main Constituents of the Earth's Atmosphere

Nitrogen	78%
Oxygen	21%
Argon	1%
Water Vapor	0-4%
Carbon Dioxide	0.037% (increasing)

Nitrogen, Oxygen, and Argon hardly interact with radiation. On the other hand water vapor and carbon dioxide both interact with infrared radiation---the type emitted by the Earth and its atmosphere.

A **greenhouse gas** is defined as a gas that absorbs significantly the radiation emitted by the Earth and its atmosphere (Infrared, IR, or longwave radiation).

Important Greenhouse Gases

(concentrations in parts per million volume)

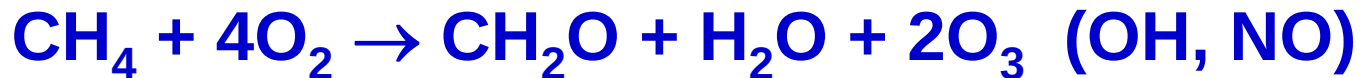
water vapor	0.1-40,000
carbon dioxide	370
methane	1.7
nitrous oxide	0.3
ozone	0.01
chlorofluorocarbons	~0.0007

Greenhouse Gases (part 1)

- Carbon dioxide (CO_2): $\sim 0.4\%$ / yr, fossil fuel combustion, photosynthesis, and ocean, ~ 380 ppmv, present value
 - Water vapor (H_2O): via temperature feedback
 - Ozone (O_3): in the troposphere ($\sim 10\%$)
-

Greenhouse Gases (related to O₃)

- Methane (CH₄): increasing human and animal populations, and change in land use (~ 1–2%/yr, ~1.7 ppmv)



- Nitrous Oxide (N₂O): Fossil fuel combustion and fertilizer denitrification (~ 0.2%/yr)

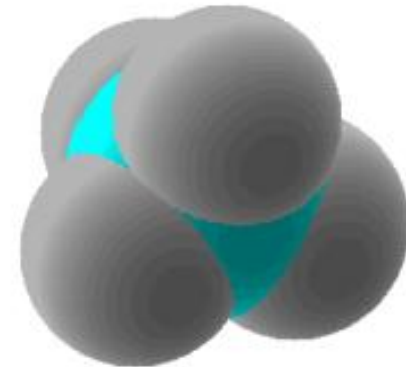


- Chlorofluorocarbons (CFCs): aerosol spray cans & refrigerant (**Montreal Protocol, 1987**)

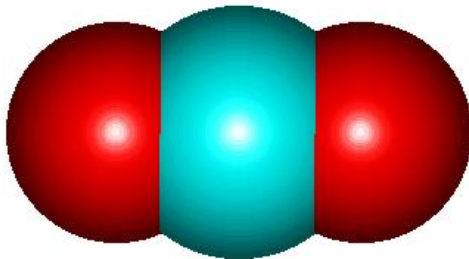


Why do certain gases interact with radiation?

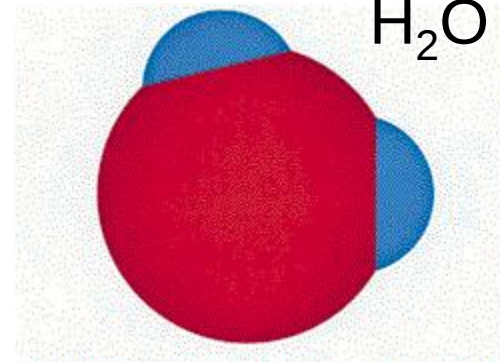
When radiation impinges on a molecule, it can excite the molecule, either by vibrating (**vibrational energy**) or rotating (**rotational energy**) it. Molecules of a particular kind of gas have a different shape from molecules of another type of gas, and so are excited by radiation in different ways.



CH₄

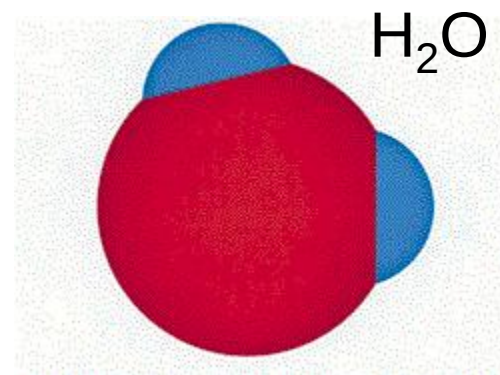
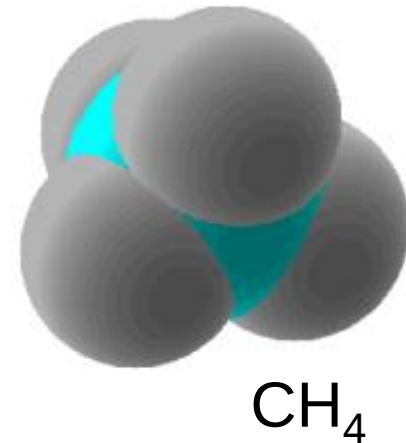
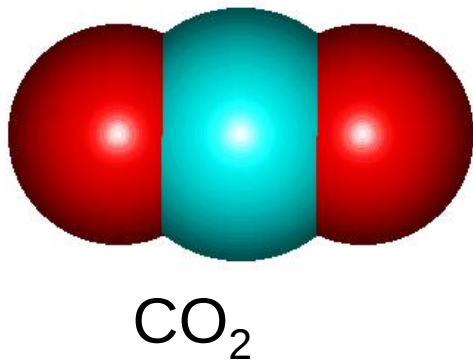


CO₂

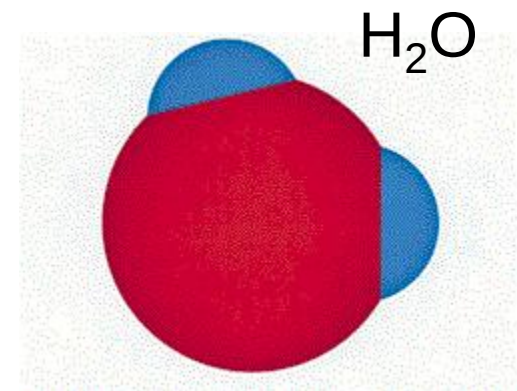
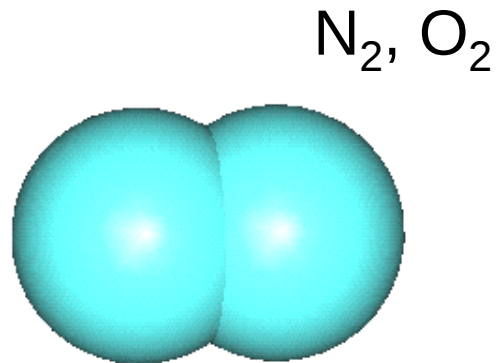
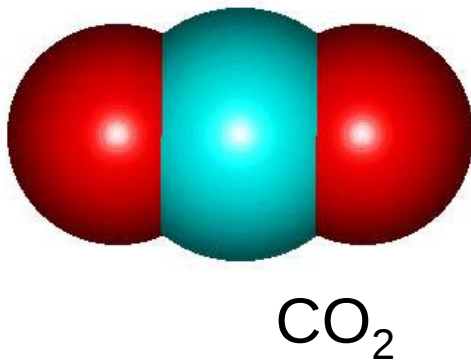
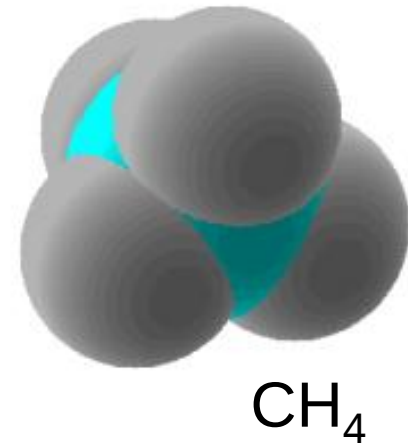


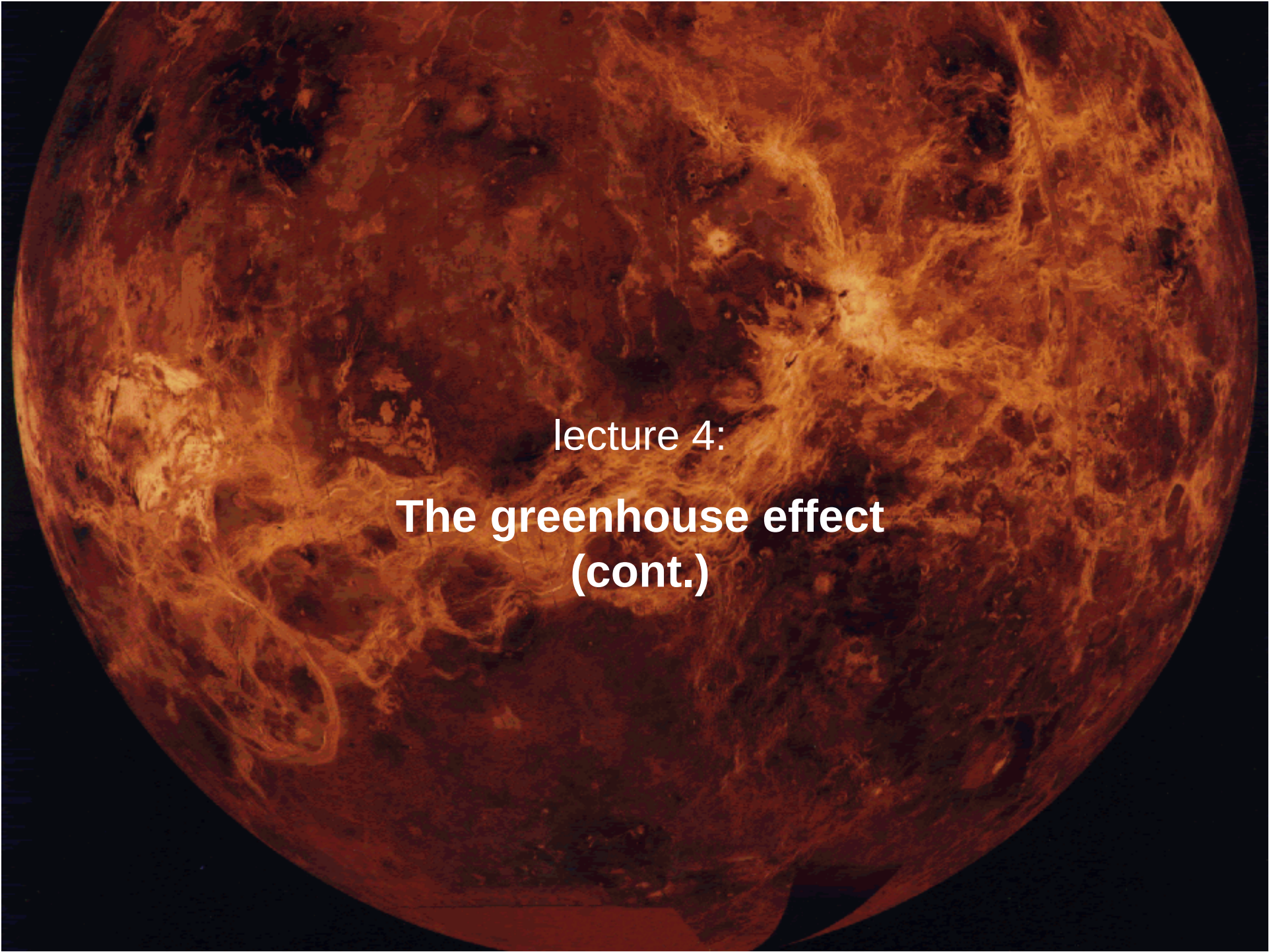
H₂O

Because of their varying geometries and sizes, different molecules absorb radiation of different wavelengths. For example, CO_2 tends to absorb radiation of a wavelength of $15\text{ }\mu\text{m}$ (this wavelength excites bending vibration of the CO_2 molecule), whereas H_2O tends to absorb at wavelengths around $16\text{-}20\text{ }\mu\text{m}$ (**rotation** of the H_2O molecule) .



Molecules with more than two atoms tend to absorb radiation more effectively than diatomic molecules such as N_2 and O_2 . This is because of the net balance of their electron configuration. That is why diatomic nitrogen and oxygen are not greenhouse gases.

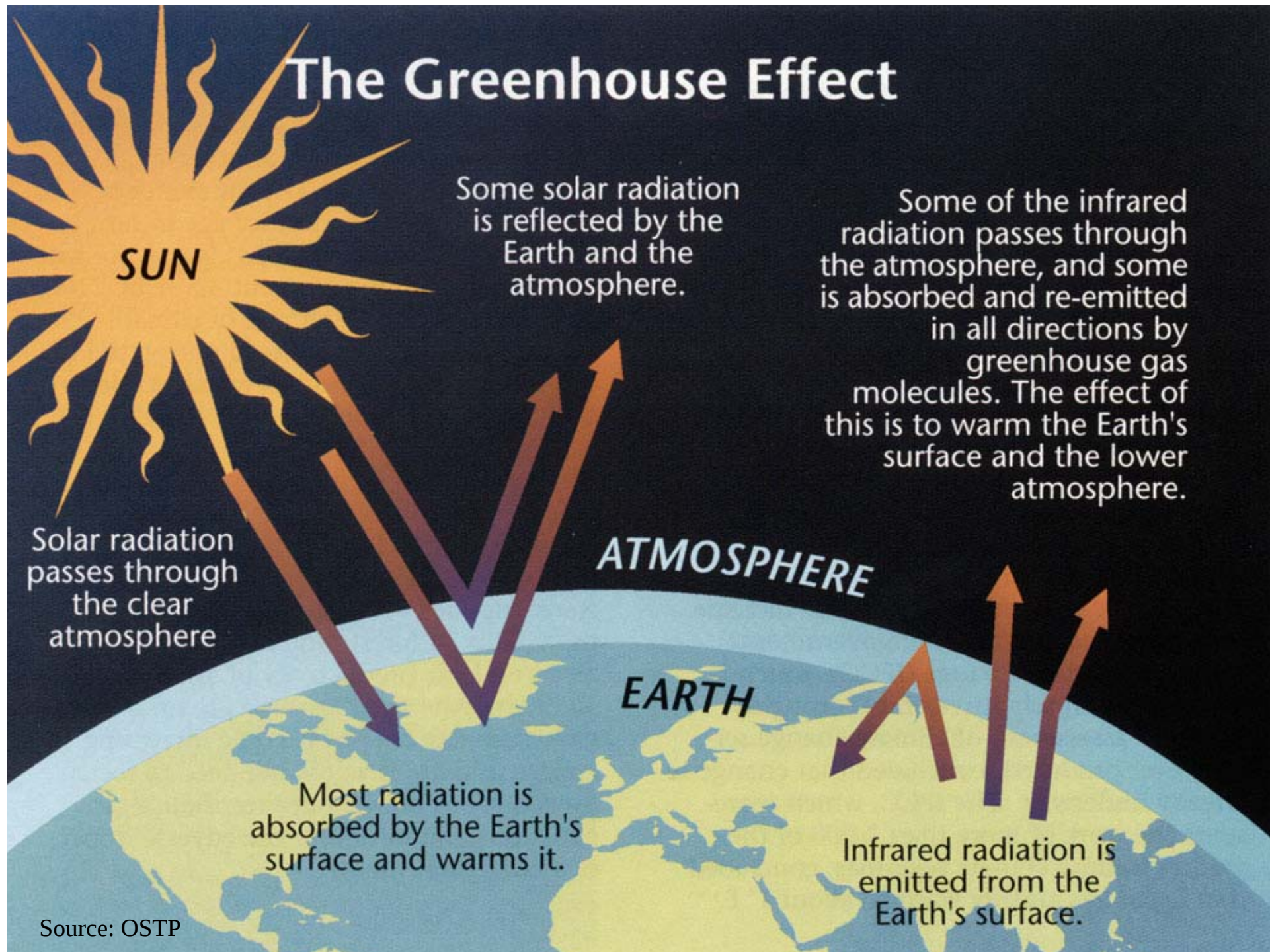




lecture 4:

**The greenhouse effect
(cont.)**

The Greenhouse Effect



Source: OSTP

A **greenhouse gas** is defined as a gas that absorbs significantly the radiation emitted by the Earth and its atmosphere (Infrared, IR, or longwave radiation).

Important Greenhouse Gases

(concentrations in parts per million volume)

water vapor	0.1-40,000
carbon dioxide	370
methane	1.7
nitrous oxide	0.3
ozone	0.01
chlorofluorocarbons	~0.0007

Vibration Modes

N_2 , O_2 , CO



CO_2 greenhouse warming

1
Symmetric

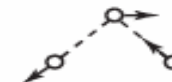
2
Bending

3
Antisymmetric

CO_2 , N_2O



H_2O , O_3



Rotation

Linear Diatomic: N_2 , O_2 , CO

Linear Triatomic: CO_2 , N_2O

Asymmetric Top (bent triatomic): H_2O , O_3

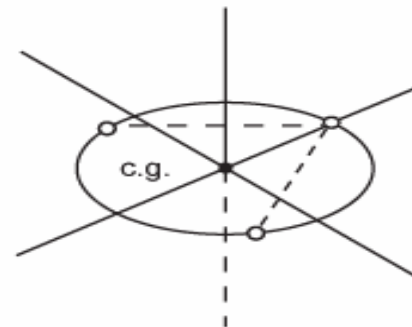
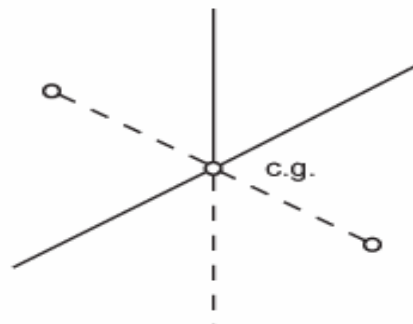
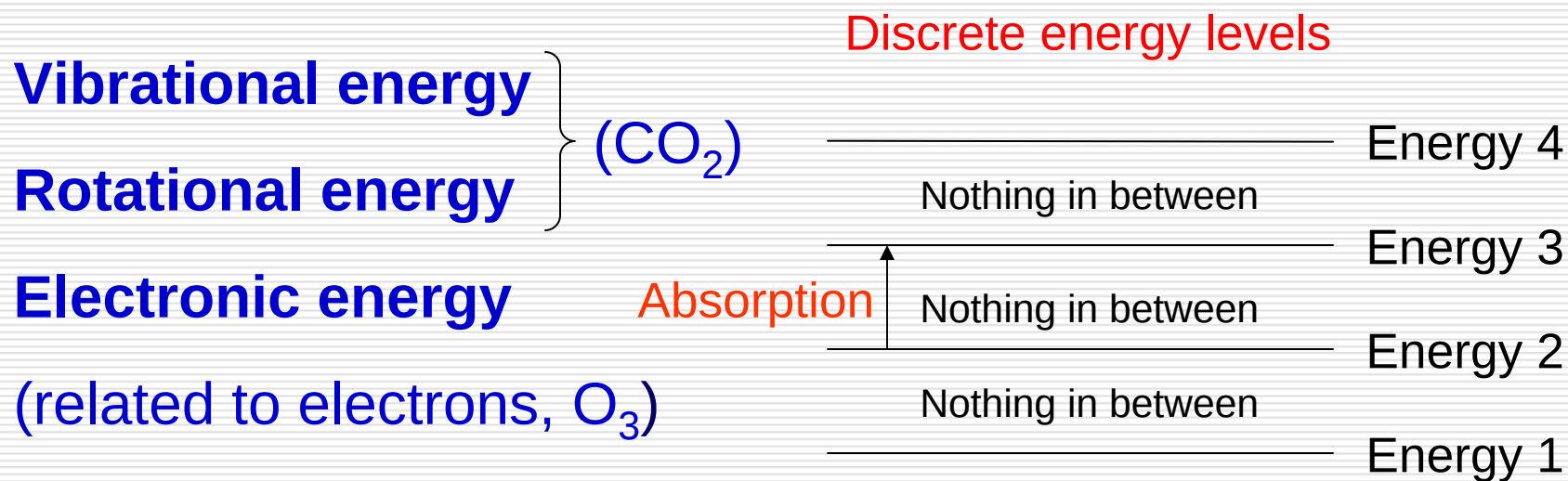


Fig. 3.3 Vibrational modes of diatomic and triatomic atmospheric molecules and the axes of rotational freedom for linear and symmetrical top molecules.

Energies of a Molecule

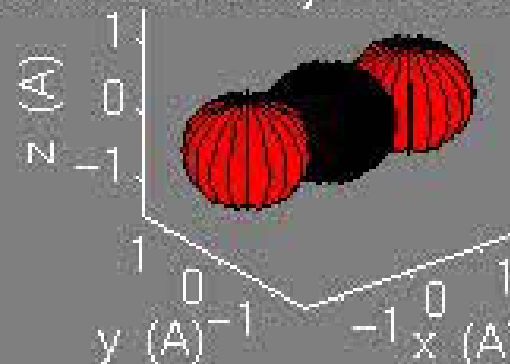
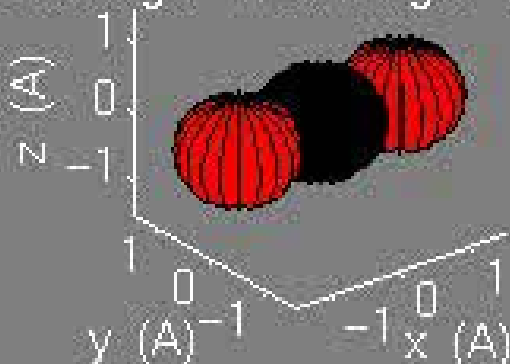


Translational energy: continuous motion (~temperature)

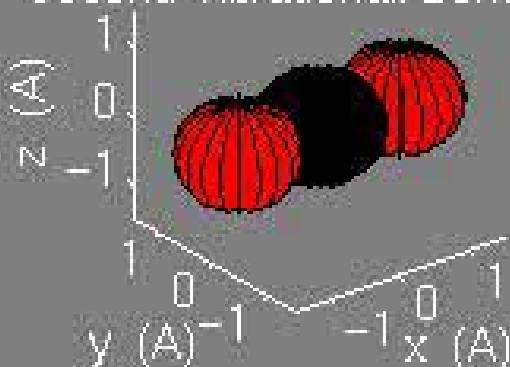


Carbon Dioxide ©PRB

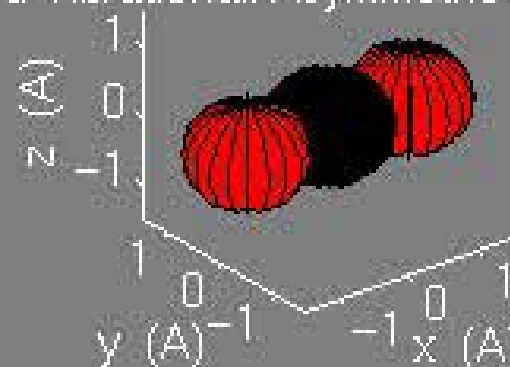
Bond length = 1.16 Å angle = 180° First Vibrational: Symmetric Stretching



Second Vibrational: Bending

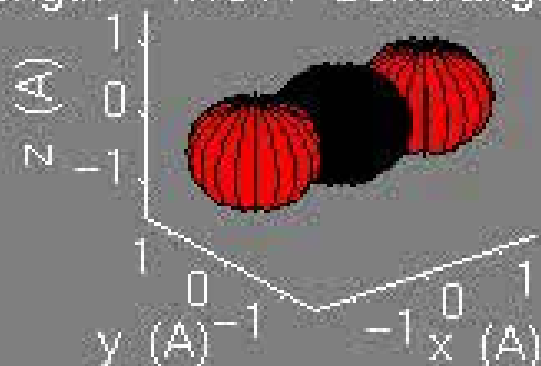


Third Vibrational: Asymmetric Stretching

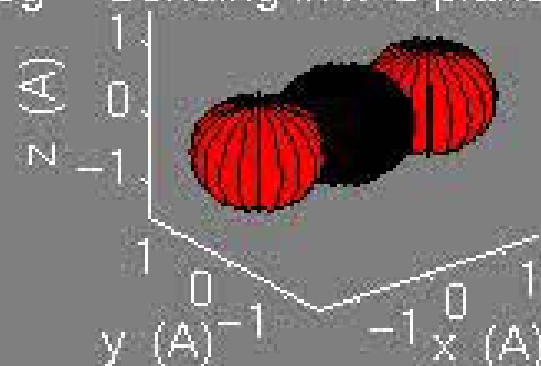


Degeneracy of Second Vibrational Mode of CO₂ ©PRB

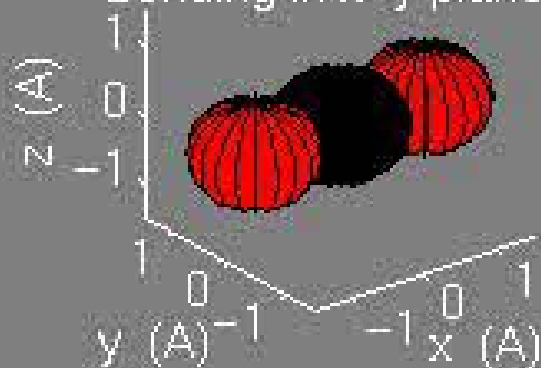
Bond length = 1.16 Å Bond angle = 180 deg



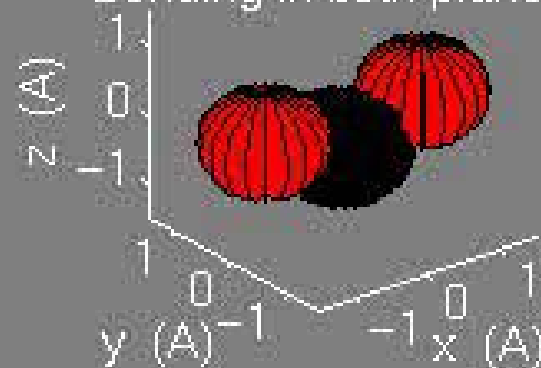
Bending in x-z plane



Bending in x-y plane

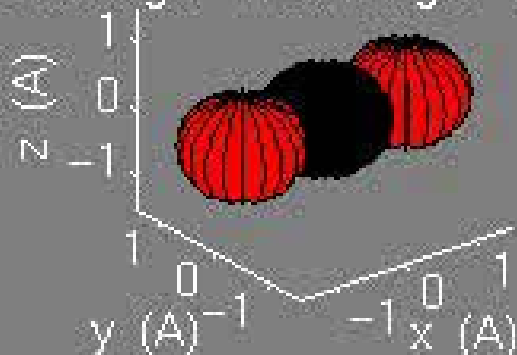


Bending in both planes

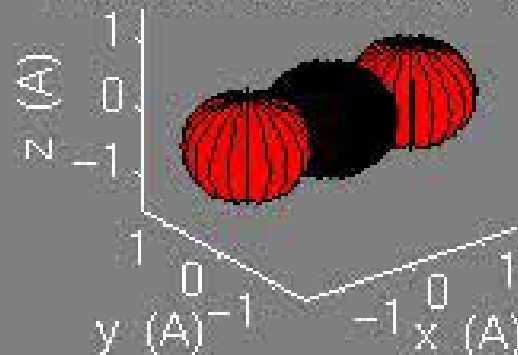


Carbon Dioxide ©PRB

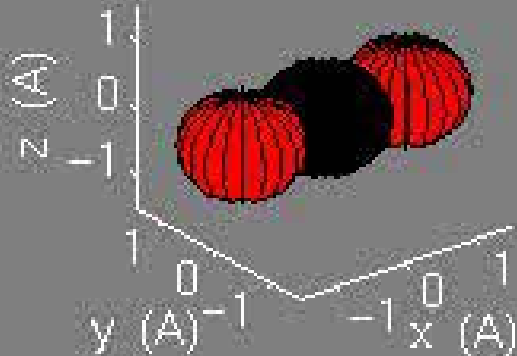
Bond length = 1.16 Å angle = 180°



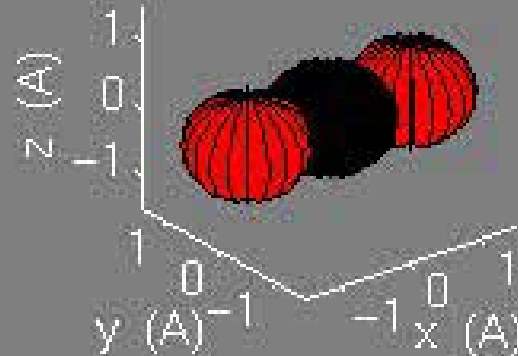
Rotation about the X-axis



Rotation about the Y-axis



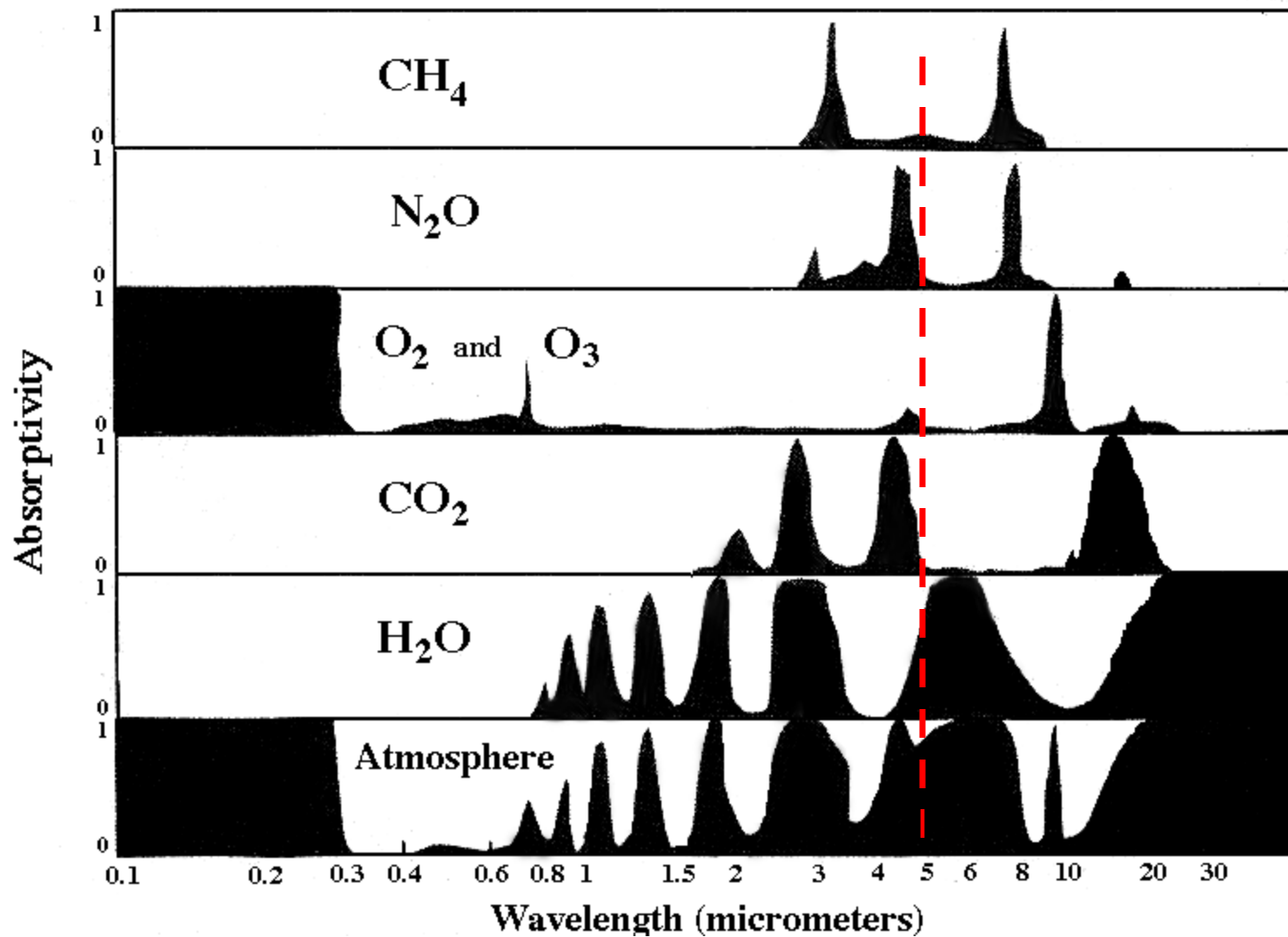
Rotation about the Z-axis

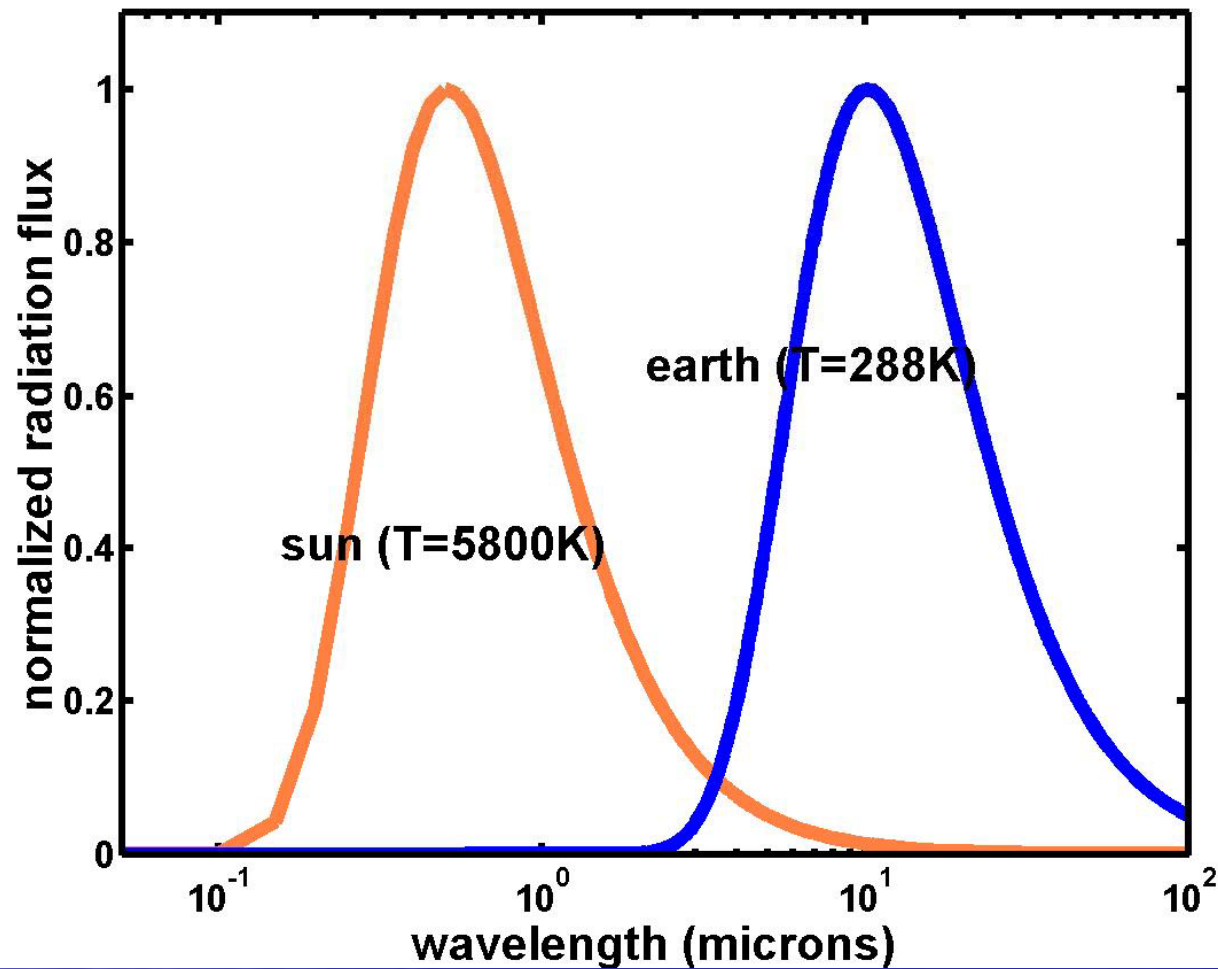


UV (.1-.4 μm) Visible (.4-.7 μm)

Thermal Infrared (>5 μm)

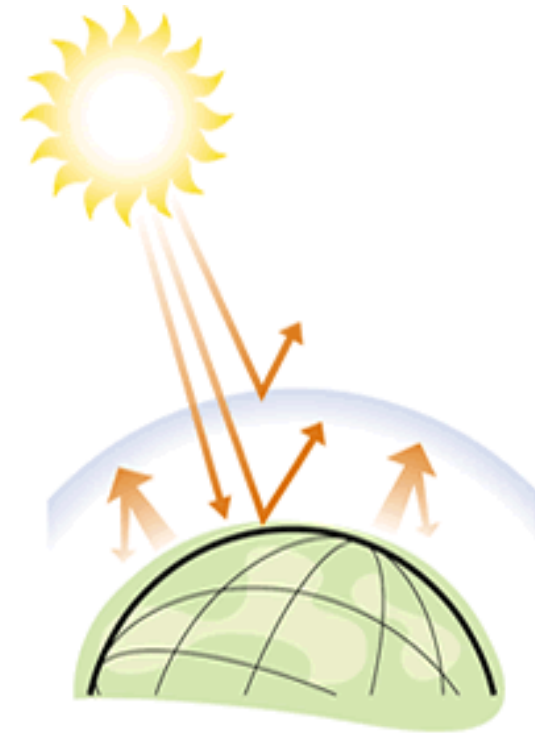
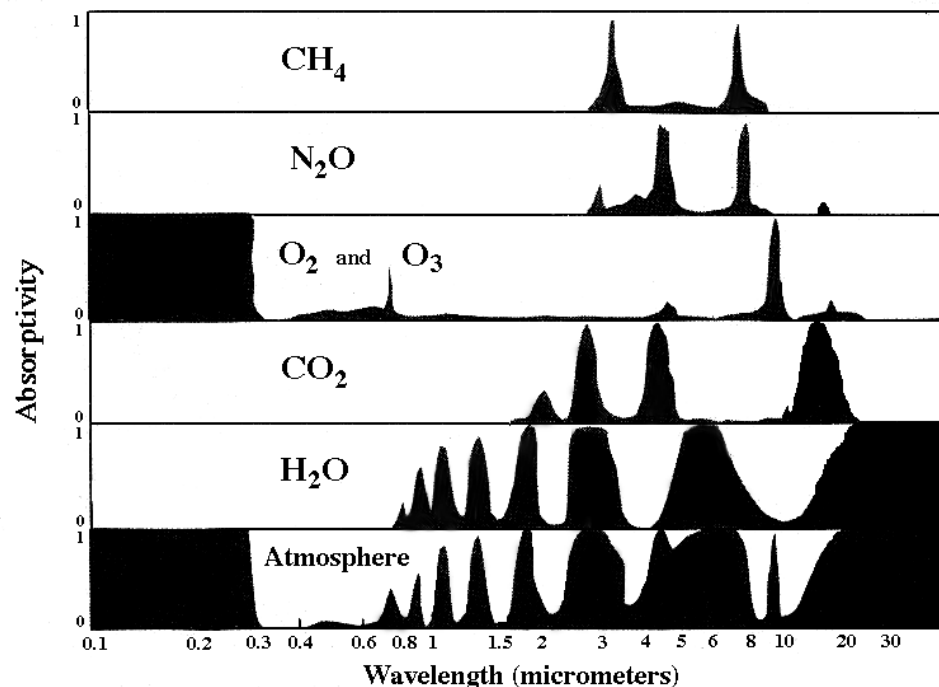
Interaction of the atmosphere with radiation





Note that the separation between the solar and terrestrial spectra occurs at about 5 μm

So how does this create a greenhouse effect? The greenhouse effect occurs because **the atmosphere is relatively transparent to the wavelengths of solar radiation, while it absorbs infrared radiation**. So a large chunk of the sun's radiation makes it to the earth's surface. At the same time, the atmosphere containing greenhouse gases absorbs the radiation emitted by the earth's surface, and re-emits it back to the surface, increasing the total energy the surface receives. This forces the earth's surface to become **warmer** than it would be otherwise.



The greenhouse effect is a **naturally-occurring** phenomenon on the earth as it is on Venus. The **enhancement** of this effect by increasing greenhouse gases associated with man-made activities is the reason for concern about climate change.

Greenhouse Gases (part 1)

- Carbon dioxide (CO_2): $\sim 0.4\%$ / yr, fossil fuel combustion, photosynthesis, and ocean, ~ 380 ppmv, present value
 - Water vapor (H_2O): via temperature feedback
 - Ozone (O_3): in the troposphere ($\sim 10\%$)
-

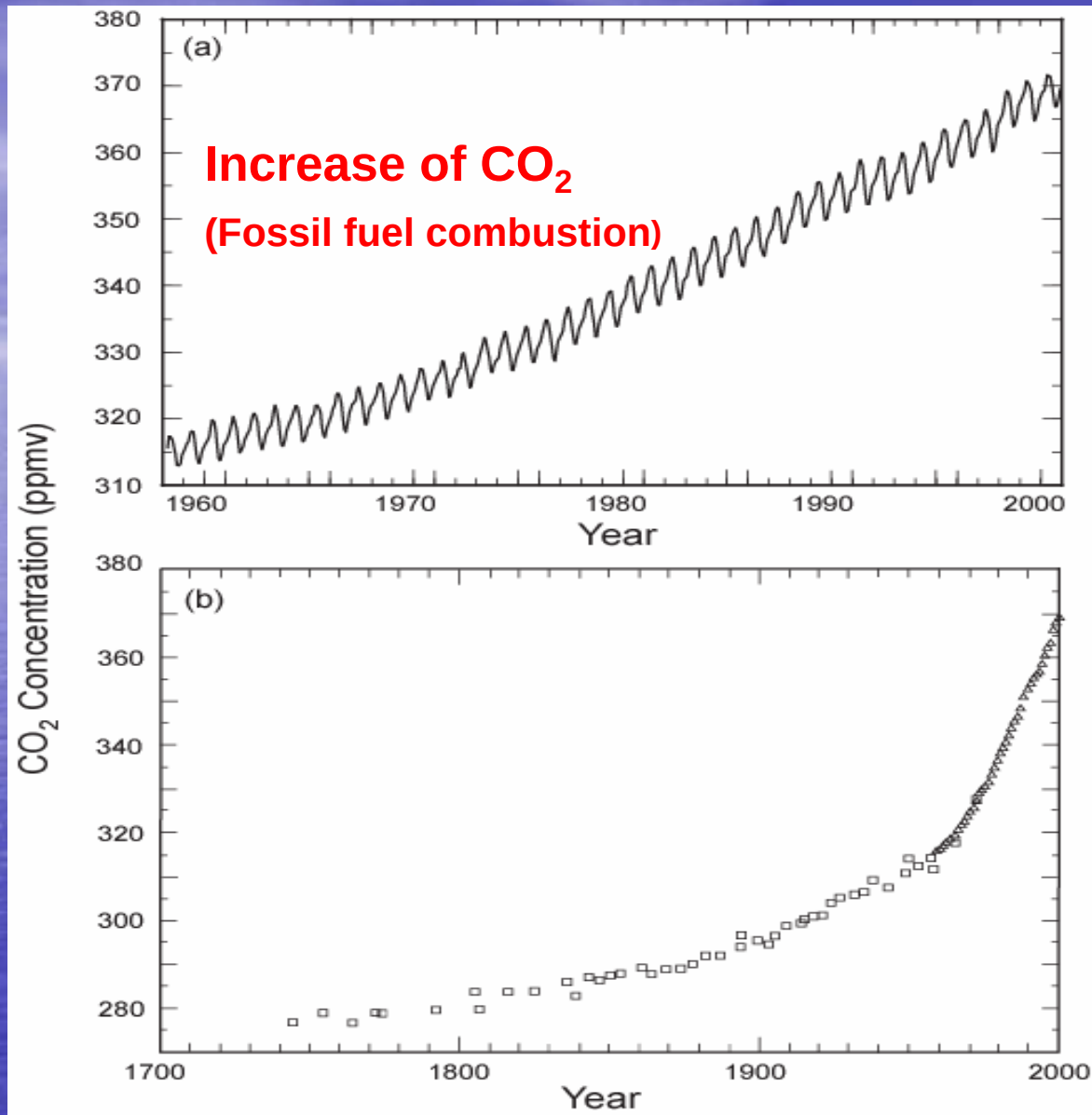
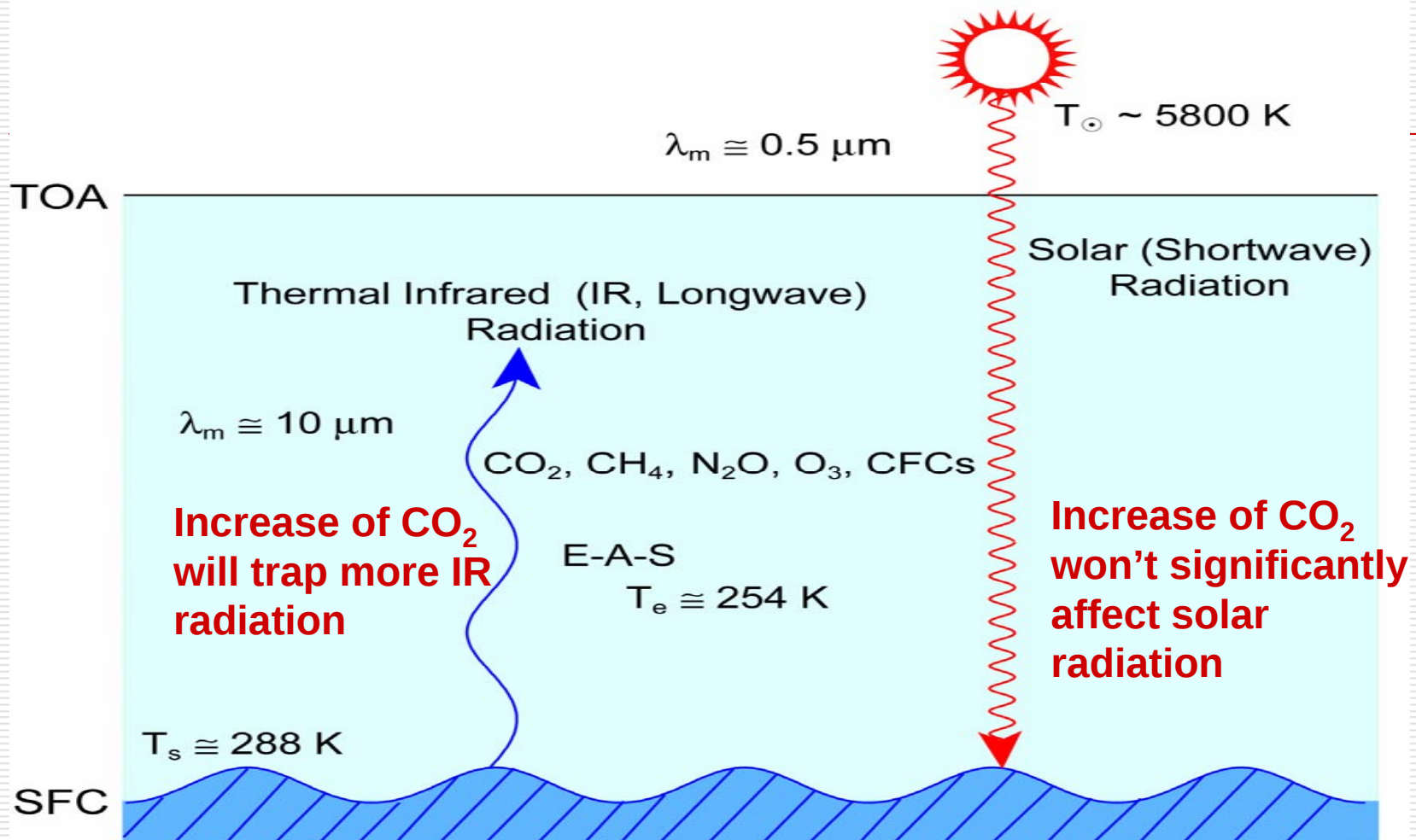


Fig. 8.11 **Concentration of atmospheric CO₂ at Mauna Loa Observatory, Hawaii**, expressed as a mole fraction in parts per million of dry air for the period 1958-2000 (courtesy of Pieter Tans, Geophysical Monitoring for Climate Change, Environmental Research Laboratory, National Oceanic and Atmospheric Administration). (b) **Atmospheric CO₂ concentration for the past 250 years** as indicated by measurements in air trapped in ice core from Antarctica determined by Neftel et al. (1985) and extended to the present using the Mauna Loa recorded displayed in (a).

Greenhouse Effect (Warming)

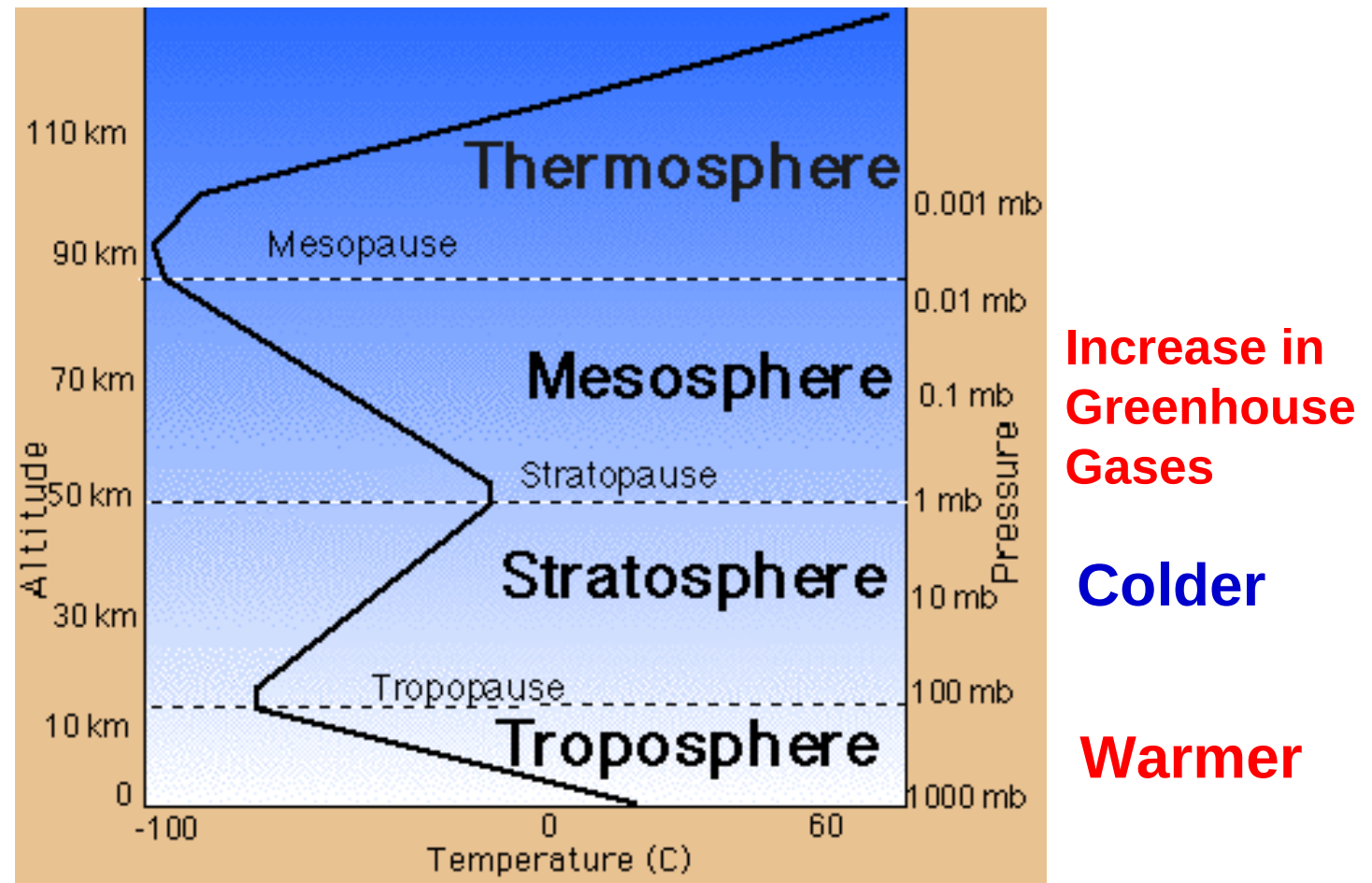


$$T_s = T_e + \gamma H$$

$$\gamma = \text{Lapse rate} \cong 6.5 \text{ K/km}$$

$$H = \text{Effective emission height} \cong 5 \text{ km}$$

Thermal structure of the atmosphere

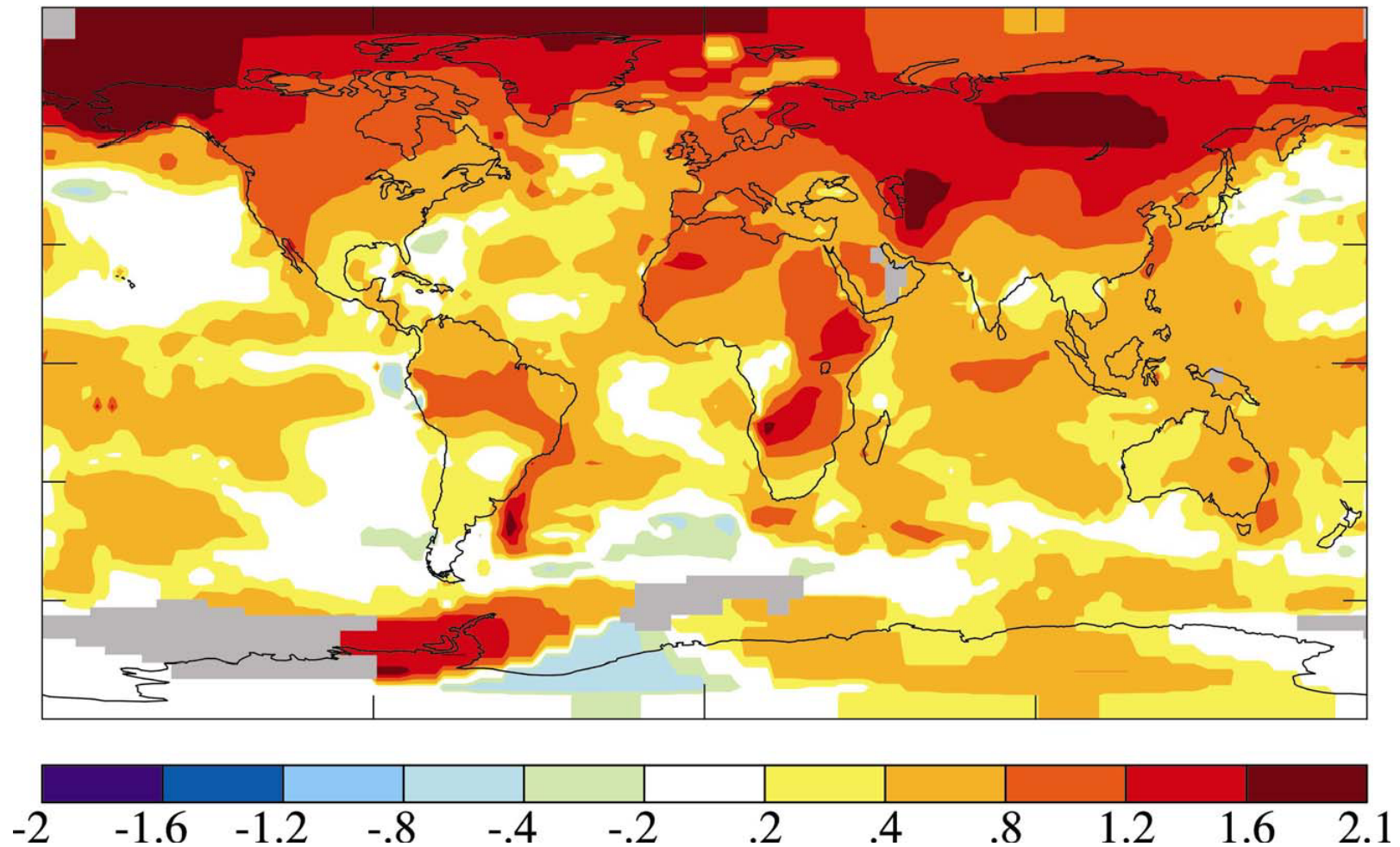


90% of the atmosphere's mass is in the troposphere.

2001-2005 Mean Surface Temperature Anomaly ($^{\circ}\text{C}$)

Base Period = 1951-1980

Global Mean = 0.53



(After James E. Hansen 2006)

Radiative Equilibrium (for extra credit)

Energy Conservation Principle at the top of the atmosphere (TOA)

Incoming solar energy absorbed = Outgoing infrared energy emitted

$$S(1-r) \times \pi a_e^2 = \sigma T_e^4 \times 4\pi a_e^2$$

where

σ = Stefan-Boltzmann constant

S = Solar constant (total solar energy/time/area at TOA)

r = Global albedo $\cong 0.3$

a_e = Radius of the Earth

T_e = Equilibrium temperature of the Earth-atmosphere-system

thus

$$T_e = [S(1-r) / 4\sigma]^{1/4}$$
